Supplementary information for Abbott *et al.*, 2016 Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment.

Supplementary figures

Questionnaires

System summaries

List of survey respondents

Table S1. Average self-rated expertise and confidence by survey and question

	Expertise	Confidence
Biomass		
Boreal Forest	3.1	2.2
Arctic Tundra	3.5	2.8
Wildfire		
Q1 Boreal Forest	3.5	2.6
Q1 Arctic Tundra	2.8	2.0
Q2 Boreal Forest	3.4	2.3
Q2 Arctic Tundra	2.6	1.7
Hydrologic C flux		
Q1 DOC	3.4	2.4
Q1 POC	2.8	2.1
Q2 DOC	3.4	2.4
Q2 POC	2.8	2.2

Experts rated themselves on a 1-5 scale for expertise and confidence for each question and biome (or parameter for the hydrologic C flux survey). Full definitions below.

The "Expertise level" scale was defined as follows: 1. I have little familiarity with the literature and I do not actively work on these particular questions. 2. I have some familiarity with the literature and I've worked on related questions but haven't contributed to the literature on this issue; it is not an area of central expertise for me. 3. I have worked on related issues and have contributed to the relevant literature but do not consider myself one of the foremost experts on this particular issue. 4. I am very familiar with relevant literature and have worked on related questions. This is an area of central expertise for me. 5. I contribute actively to the literature directly concerned with this issue, and I consider myself one of the foremost experts on it.

The "Confidence level" scale was defined as follows: 1. My answer is my best guess but I am not confident in it; it could easily be far off the mark. 2. My answer is an educated guess; it could be far off the mark, but I have some confidence in it. 3. I am moderately confident in my answer; it surely isn't precise, but it likely is in the ballpark. 4. I am confident in my answer; the true value is likely to be somewhat different from my answer, but it is unlikely to be dramatically different. 5. Given current understanding, I would be surprised if my answer were far off from the true value.

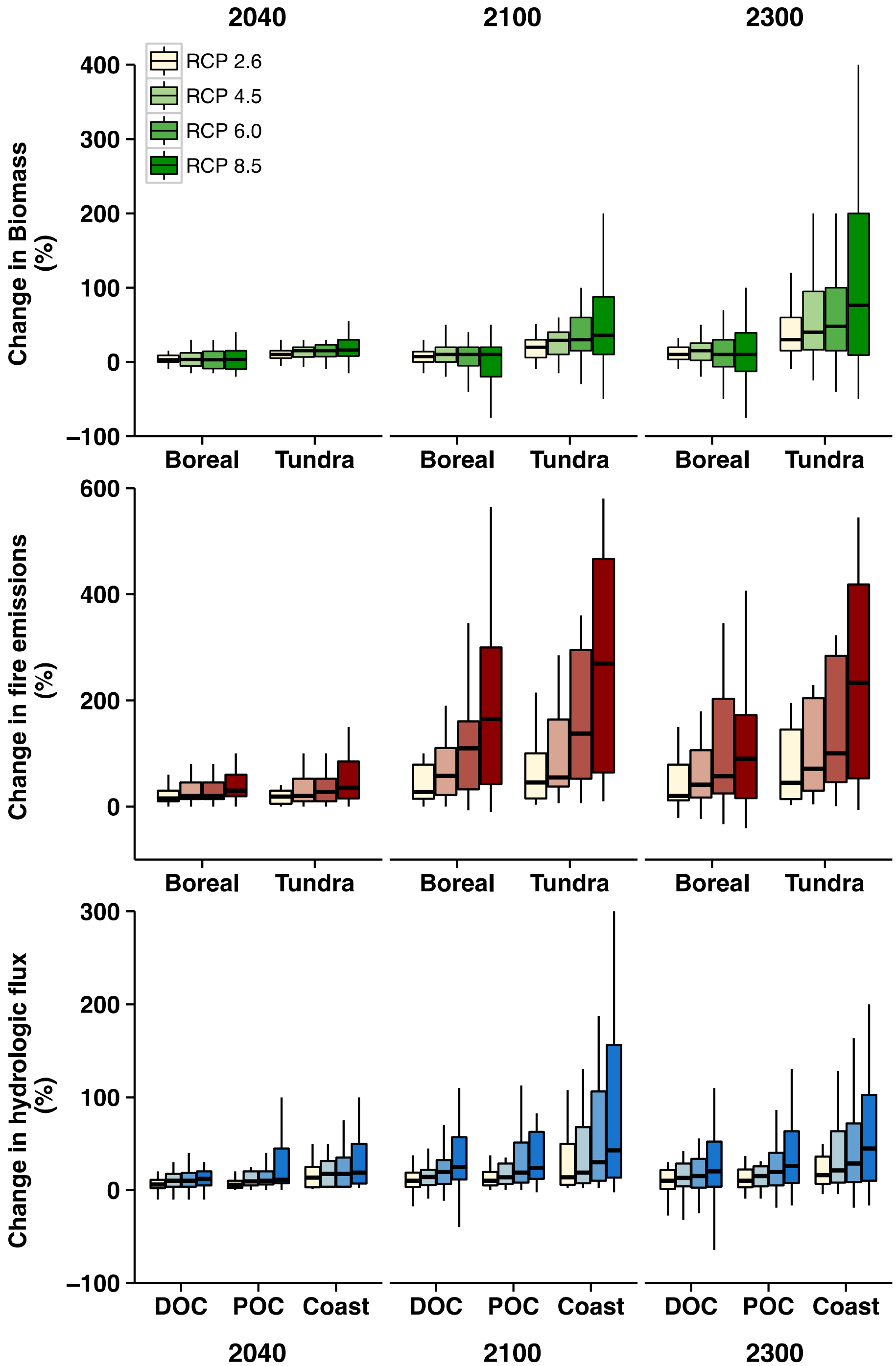

Figure S1. Change in biomass, wildfire emissions, and hydrologic carbon flux relative to current levels. Box plots represent median, quartiles, minimum and maximum within 1.5 times the interquartile range, and outliers beyond 1.5 IQR. Representative concentration pathway (RCP) scenarios range from active emissions reductions (RCP2.6) to sustained human emissions (RCP8.5).

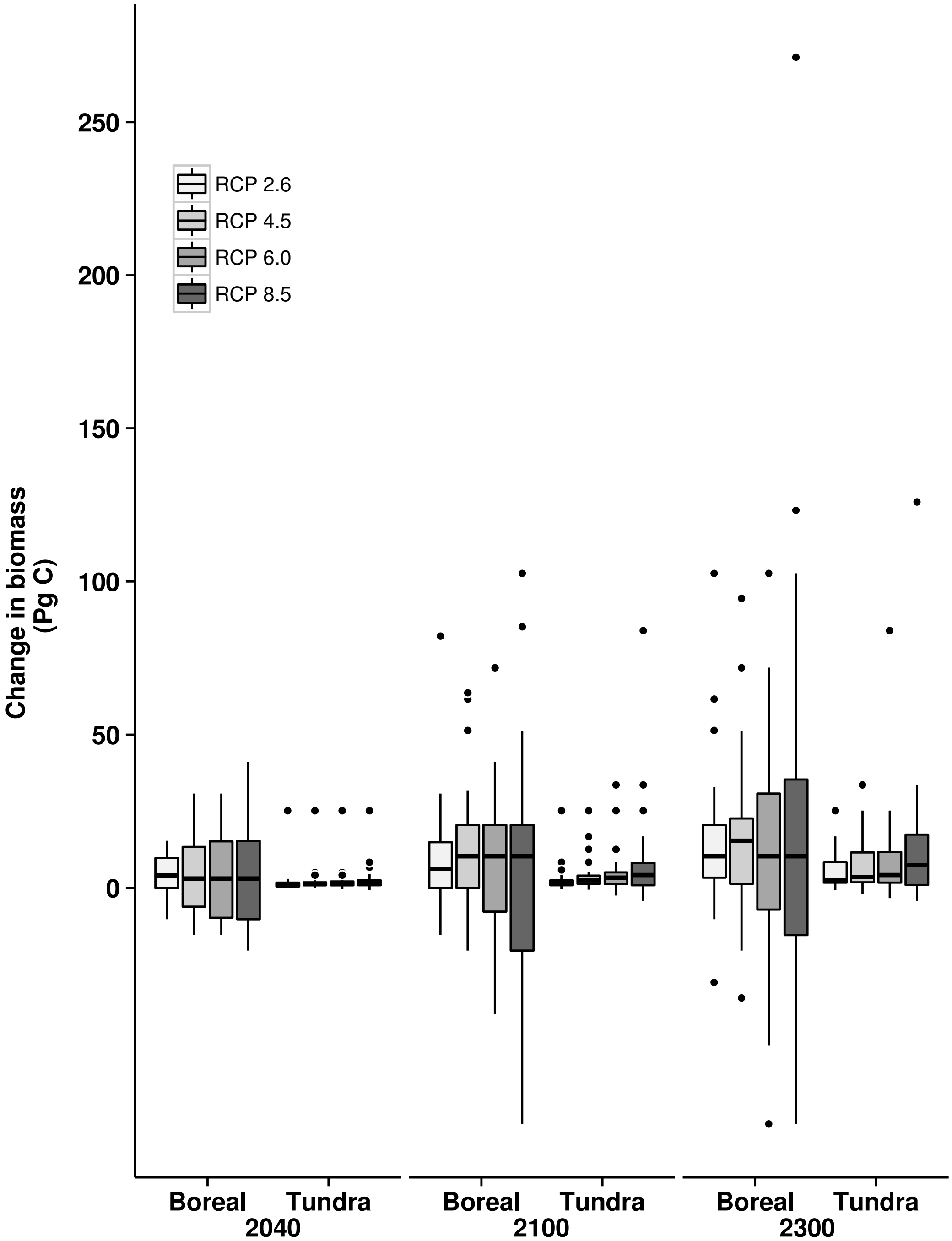

Figure S2. Distribution of biomass estimates for boreal forest and tundra at three time points and four warming scenarios. See Fig. S1 for definition of RCP scenarios and symbology.

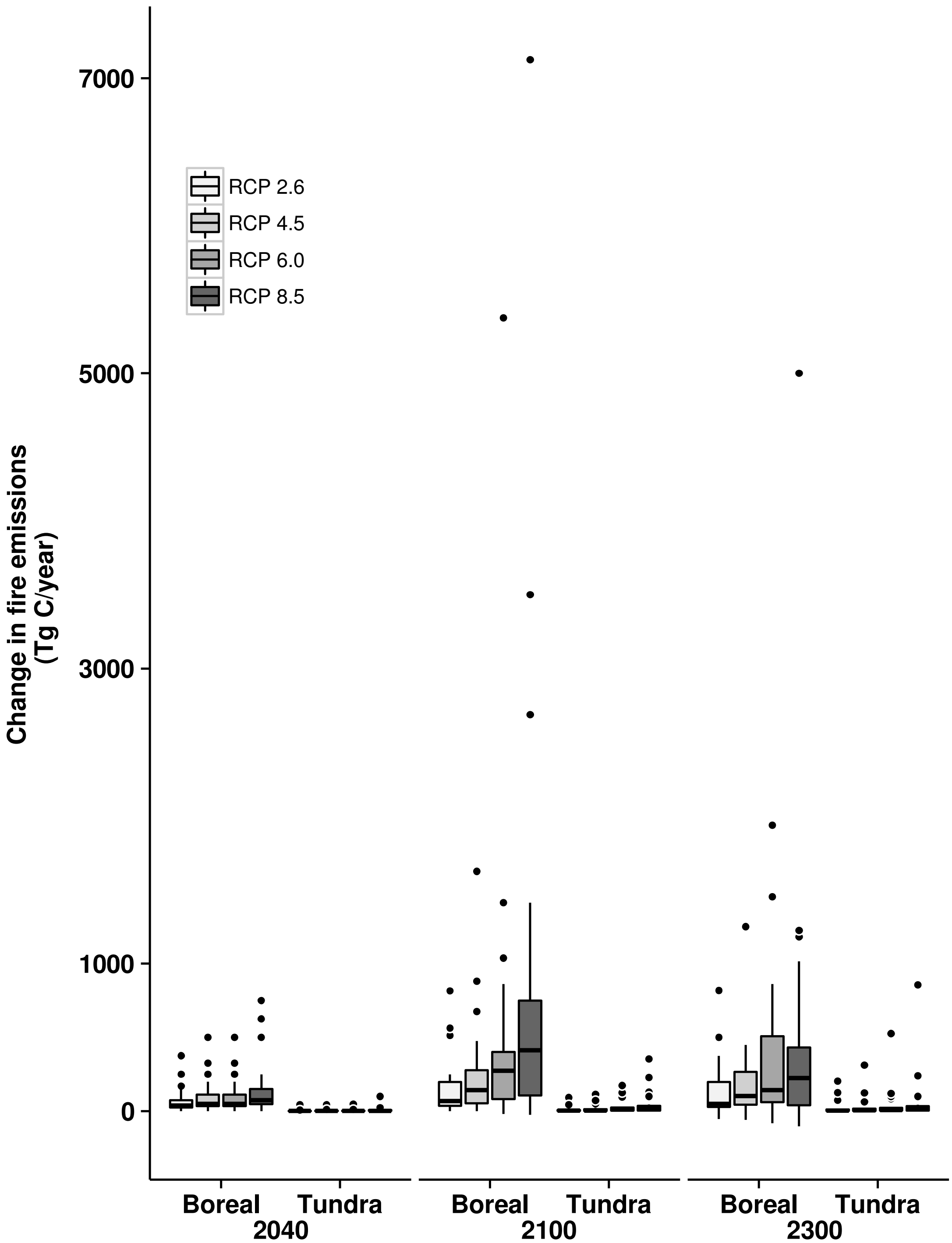

Figure S3. Distribution of wildfire estimates for boreal forest and tundra at three time points and four warming scenarios. See Fig. S1 for definition of RCP scenarios and symbology.

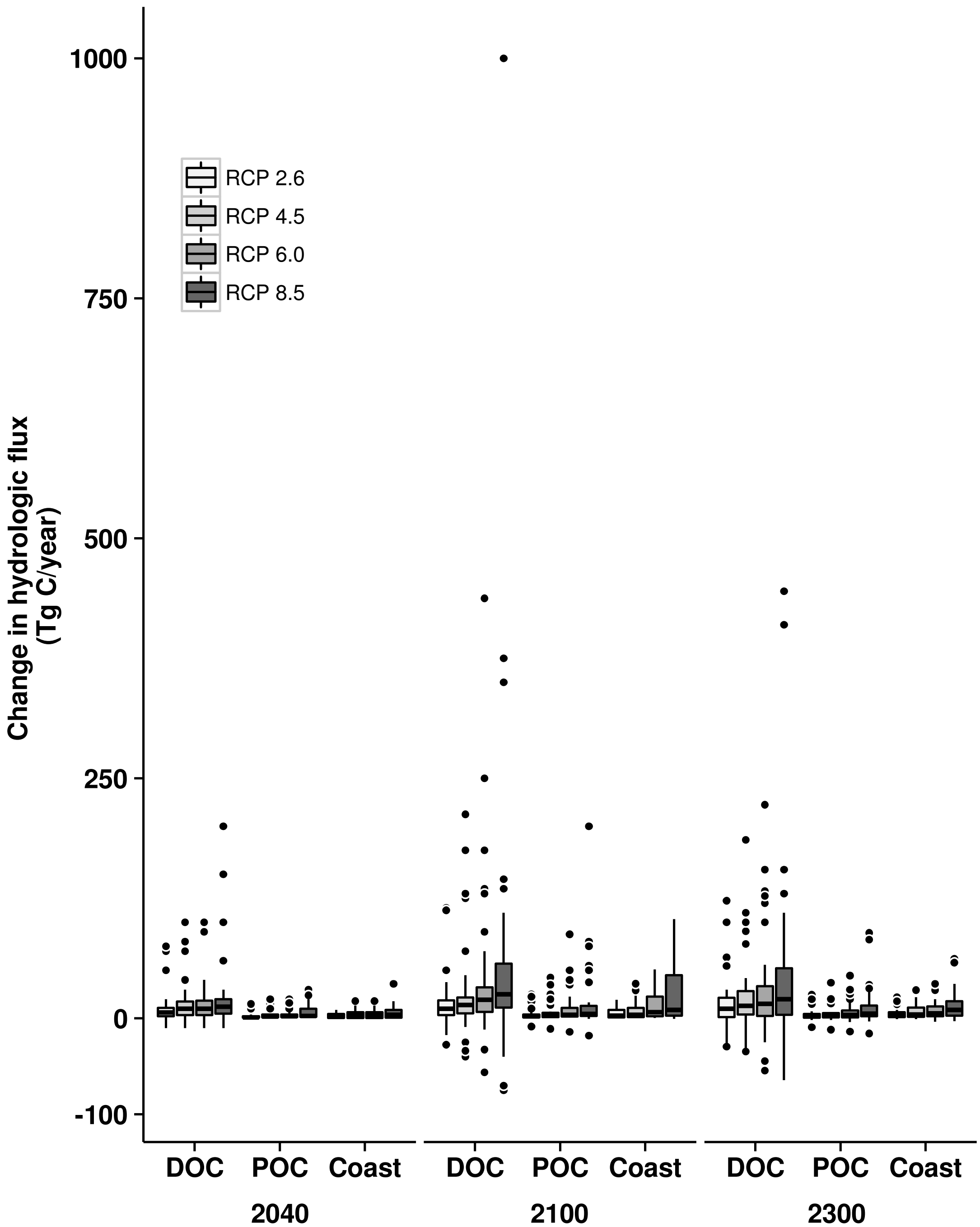

Figure S4. Distribution of hydrologic carbon flux estimates for boreal forest and tundra at three time point and four warming scenarios. See Fig. 1 for definition of RCP scenarios and symbology.

Net Ecosystem Carbon Balance of the Permafrost Region: Arctic and Boreal Biomass Survey

Introduction

The goal of this survey is to document expert opinion on the possible net ecosystem carbon balance of the permafrost region under arctic and boreal warming scenarios. Possible thresholds and tipping points in the relationship between temperature increase and high-latitude biomass are of particular interest, since such non-linearity is difficult to predict on the basis of models.

We recognize that climate-change-driven feedbacks in complex Earth systems are not, and cannot be, precisely and definitively modeled. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. By administering this survey to scientists with the most applicable expertise, we want to identify and evaluate the possible and probable magnitude of biomass response in the arctic and subarctic.

Instructions

You will be asked to provide estimates of boreal forest and arctic tundra non-soil biomass over short-term (2010-2040), medium-term (2010-2100), and long-term (2010-2300) time frames for four warming scenarios. These scenarios of regional arctic warming were generated with NCAR's Community Climate System Model (CCSM4) with inputs from the most recent IPCC radiative forcing scenarios (**Figure 1**). To minimize the possibility of misinterpretation, we have also provided a table showing the amount of warming predicted in Figure 1 by the end of each of the three time scales (**Table 1**). Climate projections, and estimates of system response, become increasingly uncertain for distant time frames. However, because carbon balance in the permafrost region can take many decades or centuries to fully respond to disturbance, we have included the 2300 time step to account for lags in this response.

In addition to answering each question, you will have a chance to indicate your level of confidence and expertise concerning your answer; and provide additional comments on how you selected your estimates. These supporting questions allow us to compare responses from multiple experts and are just as valuable as your quantitative estimates. We also ask that you identify key sources of uncertainty concerning the future response of the system (what processes missing from current models will likely play an important role, what data gaps exist, etc.), and provide any comments on how you generated your estimates. If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on professional judgment, please make a note of that.

The five-point "**Confidence level**" scale is defined as follows:

- **1=** My answer is my best guess but I am not confident in it; it could easily be far off the mark.
- **2=** My answer is an educated guess; it could be far off the mark, but I have some confidence in it.
- **3=** I am moderately confident in my answer; it surely isn't precise, but it likely is in the ballpark.
- **4=** I am confident in my answer; the true value is likely to be somewhat different from my answer, but it is unlikely to be dramatically different.
- **5=** Given current understanding, I would be surprised if my answer were far off from the true value.

The five-point "**Expertise level**" scale is defined as follows:

- **1=** I have little familiarity with the literature and I do not actively work on these particular questions.
- **2=** I have some familiarity with the literature and I've worked on related questions but haven't contributed to the literature on this issue; it is not an area of central expertise for me.

3= I have worked on related issues and have contributed to the relevant literature but do not consider myself one of the foremost experts on this particular issue.

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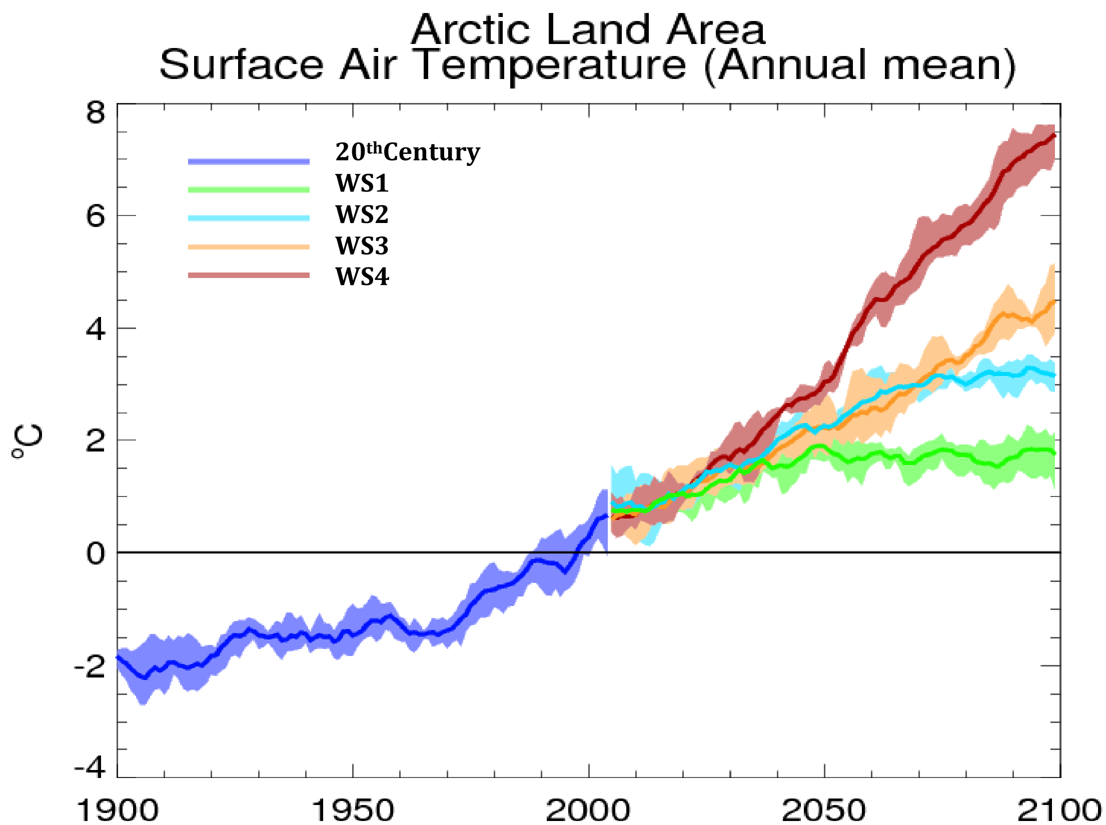

Figure 1. CCSM4: Anomaly from 1985-2004 (7-yr running average; Greenland excluded). Though not shown in this figure, temperature increase is assumed to stabilize and level off after 2100 for the purposes of this survey.

	Warming at 2040 (℃)	Warming at 2100 (℃)	Warming at 2300 (℃)
WS 1	1.5	2.0	2.0
WS 2	2.0	3.0	3.0
WS 3	2.0	4.5	4.5
WS 4	2.5	7.5	7.5

Table 1. Temperature increases for the four warming scenarios (designated here as WS 1-4). Values given represent the regional Arctic temperature increase achieved by the year indicated. Values for WS1-4 correspond to the IPCC representative concentration pathways (RCP): 2.6, 4.5, 6.0, and 8.5 respectively.

Questions

1. How much change in boreal forest and arctic tundra non-soil biomass would result from the following increases in pan-arctic mean annual surface air temperature? (Positive numbers represent % increase, negative represent % decrease).

Note: This question addresses changes in non-soil biomass for the circumpolar tundra and boreal forest due to direct climate forcing (temperature, precipitation, atmospheric CO_2, seasonality etc.) as well as indirect effects (changes in primary productivity, vegetation shifts, nutrient availability, insects, pathogens, wildfire, etc.). The table below provides estimates of current biome area and biomass. While the tundra and boreal biomes may shift over time, we are asking you to estimate biomass change for the current distribution of these biomes. For example, if biomass increased for a patch of land which currently is tundra but which becomes boreal forest, that increment would be included in your % change in biomass of arctic tundra.

	Area (10^6 km^2)[1]	**NEP (Tg C year^{-1})**[2]	**Aboveground biomass (Pg C)**[3]	**Belowground biomass (Pg C)**[4]	**Dead wood (Pg C)**[5]	**Litter (Pg C)**[6]	**Total non-soil biomass (Pg C)**
Boreal forest	13.7	500	43.6	16.1	16	27	102.7
Tundra	5.0	3.5	2.4	4.0		2	8.4

[1]Chapin et al. 2011 and Raynolds et al. 2012, [2]Pan et al. 2011 and McGuire et al. 2009, [3]McGuire et al. 2009 and Epstein et al. 2012, [4]estimated from aboveground or total biomass with ratios from Saugier et al. 2001, [5]Pan et al. 2011, [6]Pan et al. 2011 and Potter and Klooster 1997.

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **change in biomass** (% change)		**Medium-term** (2010-2100) **change in biomass** (% change)		**Long-term** (2010-2300) **change in biomass** (% change)	
	Boreal Forest	**Arctic Tundra**	**Boreal Forest**	**Arctic Tundra**	**Boreal Forest**	**Arctic Tundra**
WS1						
WS2						
WS3						
WS4						

Comments:		**Tundra expertise level (1-5)**	
		Tundra confidence level (1-5)	
		Boreal expertise level (1-5)	
		Boreal confidence level (1-5)	

What are the largest sources of uncertainty in this system's response to warming in the future?	

2. What additional comments or insights do you have concerning the content, format and implementation of this survey?

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Net Ecosystem Carbon Balance of the Permafrost Region: Tundra and Boreal Forest Wildfire Survey

Introduction

The goal of this survey is to document expert opinion on the possible net ecosystem carbon balance of the permafrost region under arctic and boreal warming scenarios. Possible thresholds and tipping points in the relationship between temperature increase and high-latitude wildfire are of particular interest, since such non-linearity is difficult to predict on the basis of models.

We recognize that climate-change-driven feedbacks in complex Earth systems are not, and cannot be, precisely and definitively modeled. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. By administering this survey to scientists with the most applicable expertise, we want to identify and evaluate the possible and probable magnitude of wildfire response in the arctic and subarctic.

Instructions

You will be asked to provide estimates of boreal and arctic wildfire over short-term (2010-2040), medium-term (2010-2100), and long-term (2010-2300) time frames for four warming scenarios. These scenarios of regional Arctic warming were generated with NCAR's Community Climate System Model (CCSM4) with inputs from the most recent IPCC radiative forcing scenarios (**Figure 1**). To minimize the possibility of misinterpretation, we have also provided a table showing the amount of warming predicted in Figure 1 by the end of each of the three time scales (**Table 1**). Climate projections, and estimates of system response, become increasingly uncertain for distant time frames. However, because carbon balance in the arctic and boreal biomes can take many decades or centuries to fully respond to disturbance, we have included the 2300 time step to account for lags in this response.

In addition to answering each question, you will have a chance to indicate your level of confidence and expertise concerning your answer; and provide additional comments on how you selected your estimates. These supporting questions allow us to compare responses from multiple experts and are just as valuable as your quantitative estimates. We also ask that you identify key sources of uncertainty concerning the future response of the system (what processes missing from current models will likely play an important role, what data gaps exist, etc.), and provide any comments on how you generated your estimates. If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on professional judgment, please make a note of that.

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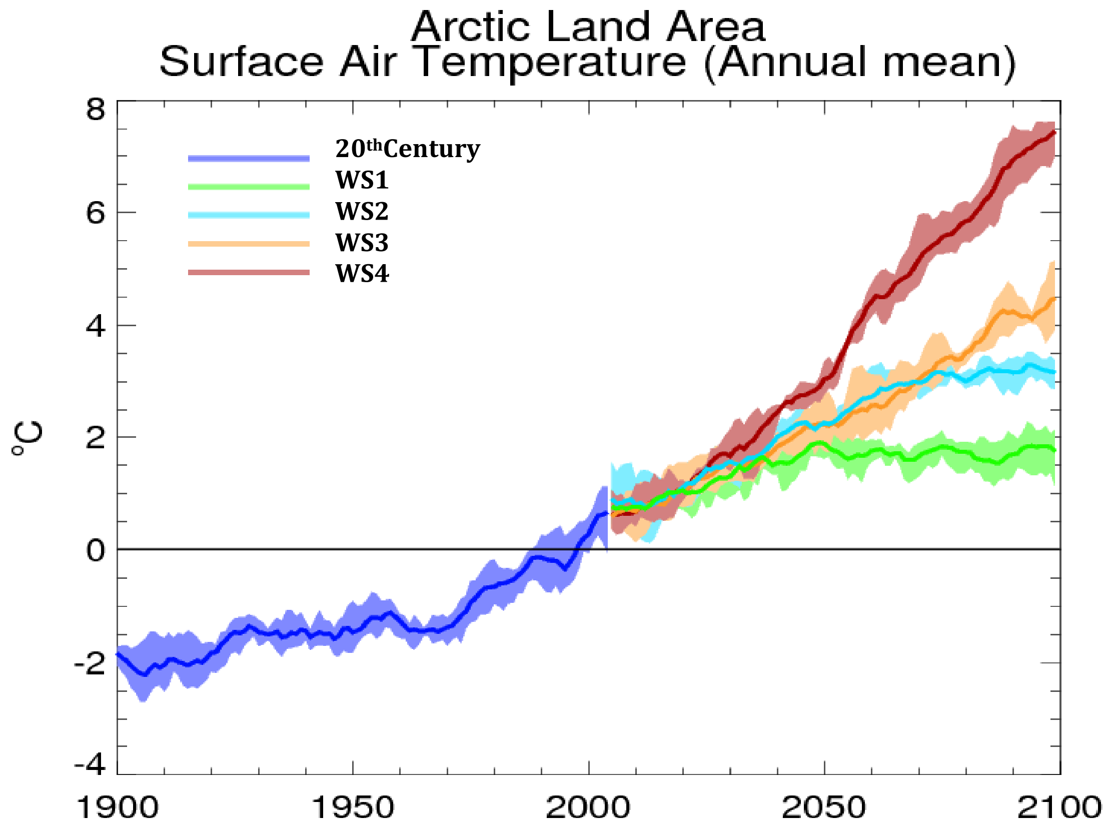

Figure 2. CCSM4: Anomaly from 1985-2004 (7-yr running average; Greenland excluded). Though not shown in this figure, temperature increase is assumed to stabilize and level off after 2100 for the purposes of this survey.

	Warming at 2040 (℃)	Warming at 2100 (℃)	Warming at 2300 (℃)
WS 1	1.5	2.0	2.0
WS 2	2.0	3.0	3.0
WS 3	2.0	4.5	4.5
WS 4	2.5	7.5	7.5

Table 1. Temperature increases for the four warming scenarios (designated here as WS 1-4). Values given represent the regional Arctic temperature increase achieved by the year indicated. Values for WS1-4 correspond to the IPCC representative concentration pathways (RCP): 2.6, 4.5, 6.0, and 8.5 respectively.

Questions

1. How much change in the annual extent of boreal and arctic wildland fire would result from the following increases in the mean annual surface air temperature in the pan-arctic? (Positive numbers represent % increase, negative represent % decrease).

Note: This question addresses changes in wildfire extent in the circumpolar boreal forest and tundra due to direct climate effects (temperature, precipitation, atmospheric CO_2, seasonality etc.) as well as indirect effects (vegetation shifts, insects, pathogens etc.).

	Boreal forest (Eurasia)	**Boreal forest (N. America)**	**Boreal forest (pan-arctic)**	**Tundra (pan-arctic)**
Area burned (km^2 yr^{-2})	64,400[1]	22,500	84,600	4,200
CO_2 emissions from fire (Tg C yr^{-2})	194	56	250	8

Boreal forest burn and emission estimates based on observed and modeled data for the period 1997-2009 (Balshi et al. 2007, Giglio et al. 2010, Hayes et al. 2011, van der Werf et al. 2010). Tundra burn and emission estimates are upscaled from Rocha et al. 2012 and Mack et al. 2011, respectively.

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **change in wildfire extent** (% change)		**Medium-term** (2010-2100) **change in wildfire extent** (% change)		**Long-term** (2010-2300) **change in wildfire extent** (% change)	
	Boreal Forest	**Tundra**	**Boreal Forest**	**Tundra**	**Boreal Forest**	**Tundra**
WS1						
WS2						
WS3						
WS4						

Comments:		**Tundra expertise level (1-5)**	
		Tundra confidence level (1-5)	
		Boreal expertise level (1-5)	
		Boreal confidence level (1-5)	

What are the largest sources of uncertainty in this system's response to warming in the future?	

[1] This estimate is slightly different from the correct value in the manuscript Table 2.

2. How much change in CO_2 release due to boreal and arctic wildland fire would result from the following increases in the mean annual surface air temperature in the pan-arctic?

Note: This question addresses changes in carbon emissions due directly to boreal and arctic wildfire. It excludes indirect carbon release due to changes in permafrost extent, net ecosystem production, biome shift, etc. Refer to Question 1 table for estimates of current emissions from wildfire.

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **CO_2 release** (% change)		**Medium-term** (2010-2100) **CO_2 release** (% change)		**Long-term** (2010-2300) **CO_2 release** (% change)	
	Boreal Forest	**Tundra**	**Boreal Forest**	**Tundra**	**Boreal Forest**	**Tundra**
WS1						
WS2						
WS3						
WS4						

Comments:			
		Tundra expertise level (1-5)	
		Tundra confidence level (1-5)	
		Boreal expertise level (1-5)	
		Boreal confidence level (1-5)	

What are the largest sources of uncertainty in this system's response to warming in the future?	

3. What additional comments or insights do you have concerning the content, format and implementation of this survey?

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Net Ecosystem Carbon Balance of the Permafrost Region: Hydrologic Carbon Flux Survey

Introduction

The goal of this survey is to document expert opinion on the possible net ecosystem carbon balance of the permafrost region under arctic and boreal warming scenarios. Possible thresholds and tipping points in the relationship between temperature increase and hydrologic carbon flux are of particular interest, since such non-linearity is difficult to predict on the basis of models.

We recognize that climate-change-driven feedbacks in complex Earth systems are not, and cannot be, precisely and definitively modeled. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. By administering this survey to scientists with the most applicable expertise, we want to identify and evaluate the possible and probable magnitude of hydrologic carbon flux in the arctic and subarctic.

Instructions

You will be asked to provide estimates of pan-arctic particulate and dissolved organic carbon flux over short-term (2010-2040), medium-term (2010-2100), and long-term (2010-2300) time frames for four warming scenarios. These scenarios of regional Arctic warming were generated with NCAR's Community Climate System Model (CCSM4) with inputs from the most recent IPCC radiative forcing scenarios (**Figure 1**). To minimize the possibility of misinterpretation, we have also provided a table showing the amount of warming predicted in Figure 1 by the end of each of the three time scales (**Table 1**). Climate projections, and estimates of system response, become increasingly uncertain for distant time frames. However, because carbon balance in the permafrost region can take many decades or centuries to fully respond to disturbance, we have included the 2300 time step to account for lags in this response.

In addition to answering each question, you will have a chance to indicate your level of confidence and expertise concerning your answer; and provide additional comments on how you selected your estimates. These supporting questions allow us to compare responses from multiple experts and are just as valuable as your quantitative estimates. We also ask that you identify key sources of uncertainty concerning the future response of the system (what processes missing from current models will likely play an important role, what data gaps exist, etc.), and provide any comments on how you generated your estimates. If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on professional judgment, please make a note of that.

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- **3=** I am moderately confident in my answer; it surely isn't precise, but it is likely in the ballpark.
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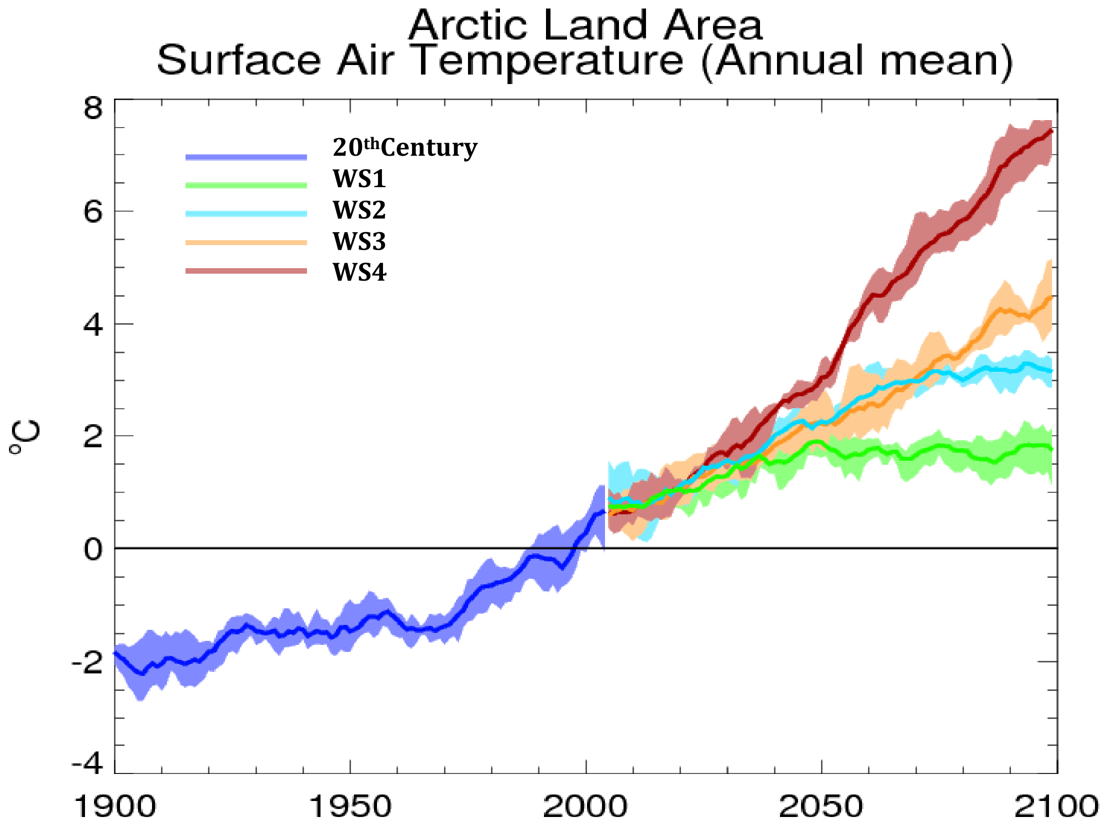

Figure 3. CCSM4: Anomaly from 1985-2004 (7-yr running average; Greenland excluded). Though not shown in this figure, temperature increase is assumed to stabilize and level off after 2100 for the purposes of this survey.

	Warming at 2040 (℃)	**Warming at 2100 (℃)**	**Warming at 2300 (℃)**
WS 1	1.5	2.0	2.0
WS 2	2.0	3.0	3.0
WS 3	2.0	4.5	4.5
WS 4	2.5	7.5	7.5

Table 1. Temperature increases for the four warming scenarios (designated here as WS 1-4). Values given represent the regional Arctic temperature increase achieved by the year indicated. Values for WS1-4 correspond to the IPCC representative concentration pathways (RCP): 2.6, 4.5, 6.0, and 8.5 respectively.

Questions

1. How much change in the amount of organic carbon delivered to freshwater ecosystems in the pan-Arctic watershed would result from the following increases in the mean annual surface air temperature in the pan-arctic? (Positive numbers represent % increase, negative represent % decrease).

Note: Questions 1 and 2 address changes in dissolved and particulate organic carbon (DOC and POC) flux in the pan-Arctic watershed (20.5 x 10^6 km^2 (Holmes et al. 2012)) due to direct climate perturbation (temperature, precipitation, etc.) as well as indirect disturbance (permafrost degradation, vegetation shift, etc.). The table below provides estimates of current DOC and POC delivery to freshwater ecosystems (lakes, rivers, and streams) and the Arctic Ocean and surrounding seas.

	DOC (Tg/yr)	Riverine POC (Tg/yr)	Coastal erosion POC (Tg/yr)
Delivery to freshwater ecosystems	100**	20	
Delivery to ocean	36*	6**	18***

*(Holmes et al. 2012), **(McGuire et al. 2009), ***sum of coastal erosion POC delivered to ocean from Vonk et al. 2012 and McGuire et al. 2009. Terrestrial to freshwater delivery of POC was calculated by dividing ocean delivery (6 Tg/yr) with the downscaled global ratio of 0.75 sedimentation of POC (Aufdenkampe et al. 2011, Battin et al. 2009, McGuire et al. 2009).

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **carbon load** (% change)		**Medium-term** (2010-2100) **carbon load** (% change)		**Long-term** (2010-2300) **carbon load** (% change)	
	DOC	**POC**	**DOC**	**POC**	**DOC**	**POC**
WS1						
WS2						
WS3						
WS4						

Comments:		**DOC Expertise level (1-5)**	
		DOC Confidence level (1-5)	
		POC Expertise level (1-5)	
		POC Confidence level (1-5)	

What are the largest sources of uncertainty in this system's response to warming in the future?	

2. How much change in the amount of organic carbon delivered to the Arctic Ocean and surrounding seas would result from the following increases in the mean annual surface air temperature in the pan-arctic? (Positive numbers represent % increase, negative represent % decrease).

Note: This question addresses changes in riverine DOC and POC flux to the ocean as well as changes in POC release from coastal erosion. The difference between the riverine to marine fluxes reported in this question and the terrestrial to freshwater fluxes reported in Question 1 represent the amount of carbon lost in transit due to mineralization and storage in sediment. Refer to the Question 1 table for estimates of current DOC and POC delivery to the Arctic Ocean and surrounding seas.

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **carbon load** (% change)			**Medium-term** (2010-2100) **carbon load** (% change)			**Long-term** (2010-2300) **carbon load** (% change)		
	DOC	**POC (riverine)**	**POC (coastal)**	**DOC**	**POC (riverine)**	**POC (coastal)**	**DOC**	**POC (riverine)**	**POC (coastal)**
WS1									
WS2									
WS3									
WS4									

Comments:		**DOC Expertise level (1-5)**	
		DOC Confidence level (1-5)	
		POC Expertise level (1-5)	
		POC Confidence level (1-5)	

What are the largest sources of uncertainty in this system's response to warming in the future?	

3. What additional comments or insights do you have concerning the content, format and implementation of this survey?

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Net ecosystem carbon balance of the permafrost region: arctic and boreal biomass background information[2]

Benjamin W. Abbott, University of Alaska Fairbanks
Michelle C. Mack, University of Florida
F. Stuart Chapin III, University of Alaska Fairbanks

Question: How will boreal forest and arctic tundra biomass change in a warmer world?

System characteristics: The boreal and arctic biomes contain 111 petagrams (Pg) carbon (C) in non-soil biomass including above and belowground living biomass, standing dead wood, and litter (see Table 1). The size and behavior of these pools depend on the balance between net primary productivity (NPP), ecosystem respiration, and disturbance such as wildfire, drought, permafrost collapse and insect outbreaks. The effect of climate change on arctic and boreal biomass depends on its direct and indirect impact on these C inputs and outputs.

The tundra biome covers 5.0 million km^2 (Raynolds et al. 2012) and the boreal forest biome covers 13.7 million km^2 (Chapin et al. 2011), though the extent of the boreal forest depends on the definition of the southern transition to temperate forest and varies in the literature from 11.4 - 18.5 million km^2 (McGuire et al. 1995, Potter and Klooster 1997, Chapin et al. 2011, Pan et al. 2011). Because most tundra falls in the continuous permafrost zone (with over 90% permafrost cover) and most boreal forest in the discontinuous, sporadic, or isolated zones (with 0-90% cover), almost all arctic tundra is underlain by permafrost, whereas most of the boreal forest is not (Zhang et al. 1999, Zhang et al. 2000).

Arctic and boreal environmental change: High latitude air temperature is increasing twice as fast as global mean temperature, due largely to feedbacks associated with sea-ice loss and decreasing snow cover (Holland and Bitz 2003, ACIA 2005, AMAP 2011, Parmentier et al. 2013). Warming has been most prevalent during the autumn and early winter in coastal areas, when sea ice is at its minimum, and in the spring at latitudes from 50° – 60° N as snow cover decreases (AMAP 2011). Precipitation has increased 5% over land north of 55° since 1950, though due to high interannual variability this trend is not significant (Peterson et al. 2006, AMAP 2011). While circumpolar precipitation minus evapotranspiration is projected to increase by 13 – 25% by 2100, much of this increase is due to changes in winter precipitation (Kattsov et al. 2007), and growing season precipitation in some areas is not expected to keep up with enhanced evapotranspiration (Chapin et al. 2010). As a result of changes in temperature and precipitation, both permafrost and non-permafrost soil temperatures have warmed over the past century, causing increased active layer thickness, freeze-thaw cycling, longer duration of thaw, and widespread ground collapse or thermokarst (Osterkamp and Romanovsky 1999, Hinkel and Nelson 2003, Osterkamp and Jorgenson 2006, Osterkamp 2007, Osterkamp et al. 2009). Models predict widespread near-surface (in the top 3 m) permafrost degradation with projections

[2] This document is not intended as a comprehensive or endorsed list of citations or information. It is a partial summary of the current understanding of biomass pools and potential changes to be used as a reference if desired while filling out the arctic and boreal biomass survey.

varying between 40 – 72 % loss by 2100 (Saito et al. 2007, Schaefer et al. 2011, Lawrence et al. 2012). Growing season length, historically 100 days for tundra and 150 days for boreal forest, has increased 2 – 4 days per decade from 1960 – 2000, due mostly to earlier spring thaw (Euskirchen et al. 2006, Chapin et al. 2011), and is projected to lengthen a total of 37 – 60 days over pre-industrial conditions by the end of the century (Euskirchen et al. 2006, Koven et al. 2011). Increased primary productivity due to CO_2 fertilization accounts for over 60% of C sequestered in the pan-boreal region over the past two decades (Balshi et al. 2007) and CO_2 fertilization is expected to strongly influence vegetation response to climate change (Schaefer et al. 2011). Wildfire extent and severity have increased throughout the permafrost region (Kasischke and Turetsky 2006, Balshi et al. 2009, Flannigan et al. 2009), including in arctic tundra (Rocha et al. 2012). The question of how arctic C balance will respond to these changes has fueled over two decades of debate (Oechel et al. 1993, Waelbroeck et al. 1997) and remains an important uncertainty with ecological and societal implications (Schaefer et al. 2011, Schuur et al. 2013).

Carbon pools: The boreal forest is estimated to contain 43.6 Pg C aboveground and 16.1 Pg C belowground in living biomass (Saugier et al. 2001, McGuire et al. 2009) and arctic tundra contains 2.4 Pg C aboveground and 4.0 Pg C belowground (Saugier et al. 2001, Epstein et al. 2012, Raynolds et al. 2012). However circumpolar estimates of living biomass, particularly belowground biomass, are coarse and uncertain (Epstein et al. 2012).

Table 1. System characteristics and non-soil biomass pools in the boreal forest and arctic tundra.

	Area (10^6 km^2)[1]	**NPP (Tg C year^{-1})[2]**	**Aboveground biomass (Pg C)[3]**	**Belowground biomass (Pg C)[4]**	**Dead wood (Pg C)[5]**	**Litter (Pg C)[6]**	**Total non-soil biomass (Pg C)**
Boreal forest	13.7	500	43.6	16.1	16	27	102.7
Tundra	5.0	3.5	2.4	4.0		2	8.4

[1]Chapin et al. 2011 and Raynolds et al. 2012, [2]Pan et al. 2011 and McGuire et al. 2009, [3]McGuire et al. 2009 and Epstein et al. 2012, [4]estimated from aboveground or total biomass with ratios from Saugier et al. 2001, [5]Pan et al. 2011, [6]Pan et al. 2011 and Potter and Klooster 1997.

In the boreal forest, living biomass density varies strongly by plant community (Hollingsworth et al. 2008), which in turn interacts with permafrost, successional stage, near-surface hydrology, topography, and micro-climate (Van Cleve et al. 1983, Camill 1999, Bakalin and Vetrova 2008, Tchebakova et al. 2009). Non-soil biomass in the boreal forest varies over two orders of magnitude from 0.3 kg m^{-2} in boreal grassland, 4.1 kg m^{-2} in spruce-lichen woodland, 10 kg m^{-2} in coniferous stands underlain by permafrost, and 25 kg m^{-2} in permafrost free mixed conifer-deciduous stands and larch forests (for detailed tables of boreal biomass see Van Cleve et al. 1983, Balshi et al. 2007, and de Groot et al. 2013). Non-soil biomass is generally lower in tundra than in boreal forest and decreases going north, with an average density of 2.5 kg m^{-2} near the boreal forest transition, down to 0.39 kg m^{-2} in the high arctic (Potter and Klooster 1997, Roy et al. 2001, Saugier et al. 2001, Epstein et al. 2012, Raynolds et al. 2012). Total non-soil biomass also decreases farther north due to diminishing landmass resulting in 80% of total tundra biomass occurring in the warmest, most southerly bioclimate zones (Raynolds et al. 2012). Some tundra types, including tussock and shrub tundra, can have 3-5 kg m^{-2} of non-soil biomass, within the range of biomass in the boreal forest (Potter and Klooster 1997, Saugier et al. 2001, Hobbie et al. 2005, Bret-Harte et al. 2013).

Standing deadwood is a relatively small (16 Pg) and potentially transient C pool due to its vulnerability to wildfire, but it can accumulate rapidly—deadwood buildup accounts for 27% of the total C sink in the boreal forest over the past two decades (Pan et al. 2011, de Groot et al. 2013). Litter is also a transient C pool but is important to C and nutrient cycles because of its fast turnover and its role as a major intermediary between biomass and soil organic matter, dissolved organic C (via leaching), and the atmosphere (via decomposition). Litter accounts for 27 Pg C in the boreal forest (Pan et al. 2011) and 2 Pg C in the tundra (Potter and Klooster 1997). Litter cycling rates depend on chemical makeup of the litter, with fast-growing species typically producing more nutrient rich and biodegradable litter (Metcalfe et al. 2011), and environmental conditions such as soil temperature and moisture (Schmidt et al. 2011, Bonan et al. 2013). Shifts in vegetation community and climate can affect the amount and rate of cycling of boreal and arctic litter and consequently nutrient and C availability in both terrestrial and aquatic ecosystems (Aerts et al. 2012, Bonan et al. 2013).

Contemporary carbon fluxes: The tundra and boreal biomes account for 10% of global gross primary production, 10 Pg yr^{-1} (McGuire et al. 2009, Tarnocai et al. 2009). Estimates of the net ecosystem C balance (based on atmospheric inversions and inventory based studies) are in good agreement that the tundra and boreal biomes sequestered 400 – 500 Tg of C and emitted 15 – 50 Tg of CH_4 annually over the last half-century (McGuire et al. 2009, Pan et al. 2011). There is high interannual variability, however, in the strength of this C sink, due largely to disturbance such as wildfire (Baker et al. 2006). The strength of the arctic C sink has also decreased by 73% when comparing the last decade with the historical record, due to increases in soil organic matter decomposition and fire (Hayes et al. 2011). Arctic tundra is a small net C sink on average over the last 25 years, taking up between 3 – 4 Tg C $year^{-1}$, though this is within the uncertainty range of field based estimates (McGuire et al. 2009). In cold, wet years tundra tends to be a net C sink while in warm, dry years it acts as a source of C to the atmosphere (McGuire et al. 2009).

Boreal and arctic biomass response to change: Boreal and arctic primary productivity and biomass may respond to climate change in two temporally distinct but causally linked ways: 1. The performance (C fixation or growth) of current vegetation communities can rapidly respond to changes in air and soil temperature, precipitation, CO_2, and nutrient availability, and 2. On a multi-decadal scale, the distribution of vegetation communities may shift in response to sustained environmental change. The short-term response of arctic biomass to climate forcing may depend primarily on the response of plant communities as they are currently distributed, while the long-term response may depend more on the ultimate redistribution of plant communities throughout the permafrost region.

Observational and experimental studies in the tundra have shown significant shifts in vegetation community, particularly in the southern extent of tundra, with trends towards increased shrub abundance (Tape et al. 2006, Myers-Smith et al. 2011, Elmendorf et al. 2012, Lantz et al. 2013). Over the past 30 years tundra biomass near the tundra-boreal transition has increased 20-26% resulting in 0.4 Pg C accumulation (Epstein et al. 2012). Movement of the tundra-taiga transition (tree line) has been complex, shifting northward in some areas at a very slow rate (McGuire et al. 2009) and staying the same or shifting southward due to anthropogenic impacts, life-history traits, fire, and changes in hydrology (Callaghan et al. 2004, Gamache and Payette 2005). Rapid transitions between steppe, tundra, and various boreal communities have happened in the past (Lloyd et al. 2006, Kienast et al. 2008) and may be accelerated by fire, permafrost collapse, and other community-replacing disturbance (Racine et al. 2004, Higuera et al. 2008, Kelly et al. 2013).

While primary productivity in the arctic is largely limited by nitrogen availability, during much of the growing season water limitation may be the ultimate control on growth (Vitousek and Howarth 1991, Chapin et al. 1995, Nasholm et al. 1998, Zhang et al. 2007, Yarie and Van Cleve 2010). Climate warming, therefore, may relieve temperature constraints on nutrient cycling, but the overall response of primary productivity and biomass may depend on how temperature and water availability interact to influence both growth and disturbance (Wookey et al. 1993, Allison and Treseder 2008, Chapin et al. 2010). Increased winter precipitation will interact with permafrost degradation-induced changes in hydrology and soil temperature to determine overall water availability in northern ecosystems. In areas where nutrient limitation is alleviated, vegetation response can be variable (Hobbie et al. 2005), and increased aboveground biomass may be partially or completely offset by belowground losses (Neff et al. 2002, Mack et al. 2004, Hartley et al. 2012).

Coupled carbon climate models vary widely in their projections of boreal and arctic vegetation response to climate change, with increases of 9 – 61 Pg C projected by 2100 (Qian et al. 2010, Koven et al. 2011, Schaefer et al. 2011, Falloon et al. 2012). Substantial increases in shrub cover and the expansion of deciduous and coniferous forest is projected in Siberia with less dramatic changes over northeastern Russia and Alaska (Falloon et al. 2012). Although projections generally agree concerning the sign of C balance, variability in the magnitude of flux is large (Ahlstrom et al. 2012) due to incomplete characterization of permafrost degradation, nutrient limitation, CO_2 fertilization, site-level hydrology, and soil moisture in model projections (Qian et al. 2010, Koven et al. 2011).

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Net ecosystem carbon balance of the permafrost region: arctic and boreal wildfire background information[3]

Benjamin W. Abbott, University of Alaska Fairbanks
Adrian V. Rocha, University of Notre Dame
Mike Flannigan, University of Alberta
Teresa N. Hollingsworth, USDA Forest Service
Merritt R. Turetsky, University of Guelph

Question: How will wildfire extent and carbon release change in the boreal forest and arctic tundra in a warmer world?

System characteristics: Wildfires burn on average 84,600 km^2 yr^{-2} in the boreal forest and 4,200 km^2 yr^{-2} in arctic tundra (Balshi et al. 2007, Giglio et al. 2010, Hayes et al. 2011, Rocha et al. 2012). This accounts for 10 % of global carbon emissions from fire (Table 1; van der Werf et al. 2010, Mack et al. 2011). Rapid environmental change at high latitudes is affecting both physical and ecosystem controls on wildfire including temperature, precipitation, evapotranspiration, lightning ignition, human ignition, permafrost thaw depth, vegetation distribution, insect outbreaks, and drought stress (ACIA 2004, AMAP 2011). High-latitude wildfire extent and emissions are projected to increase with climate change across most of the boreal and arctic regions (Flannigan et al. 2009, Joly et al. 2012). Increased wildfire has implications for local ecosystems and the global carbon cycle, however important uncertainties persist concerning the magnitude and timing of the response of boreal and arctic wildfire to climate change (Barrett et al. 2012, Kelly et al. 2013).

Wildfire affects ecosystem functioning and structure in both arctic tundra and boreal forest across the circumpolar north (Kasischke and Turetsky 2006), though the role of fire varies by biome and continent (Chambers et al. 2005, de Groot et al. 2013). The tundra biome covers 5.0 million km^2 (Raynolds et al. 2012) and the boreal forest biome covers 13.7 million km^2 (Chapin et al. 2011), though the extent of the boreal forest depends on the definition of the southern transition to temperate forest and varies in the literature from 11.4 – 18.5 million km^2 (McGuire et al. 1995, Potter and Klooster 1997, Chapin et al. 2011, Pan et al. 2011). Because most tundra falls in the continuous permafrost zone (with over 90% permafrost cover) and most boreal forest in the discontinuous, sporadic, or isolated zones (with 0-90% cover), almost all arctic tundra is underlain by permafrost, whereas most of the boreal forest is not (Zhang et al. 1999, Zhang et al. 2000).

Arctic and boreal environmental change: High latitude air temperature is increasing twice as fast as global mean temperature, due largely to feedbacks associated with sea-ice loss and decrease in snow cover (Holland and Bitz 2003, ACIA 2005, AMAP 2011). Warming has been most prevalent during the autumn and early winter in coastal areas, when sea ice is at its

[3] This document is not intended as a comprehensive or endorsed list of citations or information. It is a partial summary of the current understanding of high-latitude wildfire and potential changes to be used as a reference if desired while filling out the arctic and boreal wildfire survey.

minimum, and in the spring at latitudes from 50° – 60° N as snow cover decreases (AMAP 2011). Growing season length, historically 100 days for tundra and 150 days for boreal forest, has increased 2 – 4 days per decade from 1960 – 2000, due mostly to earlier spring thaw (Euskirchen et al. 2006, Chapin et al. 2011), and is projected to lengthen a total of 37 – 60 days over pre-industrial conditions by the end of the century (Euskirchen et al. 2006, Koven et al. 2011). Changes in temperature and precipitation have warmed both permafrost and non-permafrost soils over the past century, causing a thicker active layer, more intense freeze-thaw cycles, longer duration of thaw, and widespread ground collapse or thermokarst (Osterkamp and Romanovsky 1999, Hinkel and Nelson 2003, Osterkamp and Jorgenson 2006, Osterkamp 2007, Osterkamp et al. 2009). Models predict a 40 – 72 % loss of near-surface permafrost (in the top 3 m) by 2100 (Saito et al. 2007, Schaefer et al. 2011, Lawrence et al. 2012). Annual precipitation minus evapotranspiration is expected to increase by 13 – 25 % by 2100, driven primarily by increased winter precipitation (Holland et al. 2007, Kattsov et al. 2007). However, soil and vegetation moisture are expected to decrease, due to an intensification of the hydrologic cycle, including warmer summer temperature, increased evapotranspiration, and changes in infiltration due to permafrost degradation (Hinzman et al. 2005, Rawlins et al. 2010), with some areas, such as Alaska experiencing regional drying (Chapin et al. 2010). Wildfire severity, defined as the proportion of aboveground biomass consumed during combustion (Keeley 2009), and extent have increased throughout the permafrost region (Kasischke and Turetsky 2006, Balshi et al. 2009a, Flannigan et al. 2009), including in arctic tundra (Rocha et al. 2012).

Arctic and boreal vegetation has already been influenced by recent changes in climate, including precipitation, temperature, growing season length, CO_2 fertilization, and increased disturbance such as fire and insect outbreaks (Sturm et al. 2001, Goetz et al. 2005, McGuire et al. 2009, Kelly et al. 2013). Increased primary productivity due to CO_2 fertilization accounts for over 60 % of carbon (C) sequestered in the pan-boreal region over the past two decades (Balshi et al. 2007) and is expected to strongly influence vegetation response to climate change (Schaefer et al. 2011). Observational and experimental studies in tundra have shown significant vegetation community shifts, particularly along the southern transition to boreal forest, with trends towards increased shrub abundance (Tape et al. 2006, Myers-Smith et al. 2011, Elmendorf et al. 2012, Lantz et al. 2013). Over the past 30 years, tundra biomass near the tundra-boreal transition has increased 20 – 26 % resulting in 400 Tg C accumulation (Epstein et al. 2012). Movement of the tundra-taiga transition (tree line) is complex, shifting northward in some areas at a very slow rate (McGuire et al. 2009) and staying the same or shifting southward due to fire, anthropogenic impacts, life-history traits, and changes in hydrology in others (Callaghan et al. 2004, Gamache and Payette 2005, Payette et al. 2008). Rapid transitions between steppe, tundra, and various boreal communities have happened in the past (Lloyd et al. 2006, Higuera et al. 2008, Kienast et al. 2008) and may be accelerated by fire, permafrost collapse, and other community-replacing disturbance (Racine et al. 2004, Girardin et al. 2013, Kelly et al. 2013).

Boreal and arctic wildfire extent and carbon emissions: Fire is the dominant type of ecosystem disturbance in the boreal forest, affecting forest and peatland ecosystems (Soja et al. 2004, Kasischke and Turetsky 2006), and it appears to be increasing in arctic tundra (Higuera et al. 2011). The fire regime in the boreal forest is characterized by high interannual variability, with fire extent varying over 400 % interannually, and areal C emissions varying over an order of magnitude (Soja 2004, Giglio 2010, Hayes 2011). In both boreal and tundra systems, fire regime is determined primarily by weather, ignition, and vegetation (Flannigan et al. 2005, Higuera et al.

2011, Parisien et al. 2011, Rocha et al. 2012), with weather explaining most of the short-term variance in area burned (Gillett et al. 2004, Cary et al. 2006, Balshi et al. 2009b, Hu et al. 2010). Fire in the boreal forest can be influenced by permafrost and associated soil drainage (Harden et al. 2000, Turetsky et al. 2011), climate (Chapin et al. 2000), and vegetation (Girardin et al. 2013, Kelly et al. 2013). Tundra fire can be limited by burnable aboveground biomass, particularly in barrens and the high arctic (Higuera et al. 2008, Rocha et al. 2012), and temperature and precipitation during the growing season where adequate fuel is present (Hu et al. 2010).

	Boreal forest (Eurasia)	**Boreal forest (N. America)**	**Boreal forest (total)**	**Tundra (total)**
Area burned (km^2 yr^{-2})	62,100	22,500	84,600	4,200
CO_2 emissions from fire (Tg C/yr)	194	56	250	8

Table 1. Boreal forest burn and emission estimates based on observed and modeled data for the period 1997-2009 (Balshi et al. 2007, Giglio et al. 2010, Hayes et al. 2011, van der Werf et al. 2010). Tundra burn and emission estimates are upscaled from Rocha et al. 2012 and Mack et al. 2011, respectively. Considerable uncertainty remains around these estimates.

Carbon emissions from fire depend on pre-fire biomass, soil organic matter, bulk density and depth of burn. In both boreal forest and tundra, fires typically consume 5 – 30 % of ecosystem C (Kasischke et al. 2000, van der Werf et al. 2010, Mack et al. 2011). Biomass available for combustion varies by stand type (see de Groot et. al 2010 for detailed Canadian and Russian tree and forest floor fuel loads), with average combustion of 2662 and 1979 g C m^{-2} in boreal North America and boreal Eurasia, respectively (van der Werf et al. 2010). Emissions vary from 256 g C m^{-2} in the East Boreal Shield of Canada to 5110 g C m^{-2} in larch forests of Siberia (Balshi et al. 2007). Despite this large range, landscape-level carbon emissions depend more on fire extent than vegetation type or burn severity for most ecotypes (Amiro et al. 2009). CO_2 is the predominant C gas released from fire, however, CO and CH_4 can account for 8 and 4 % of total carbon emissions during flaming combustion, and 20 and 11 %, respectively, during smoldering combustion (French et al. 2002). Across the boreal forest, CO makes up 14 % and CH_4 makes up 1 % of total carbon emissions (Kasischke and Bruhwiler 2002), with another ~1 % of emissions coming from non-methane volatile organic compounds (Simpson et al. 2011).

There is strong continental divergence in tree species and associated fire regime between the boreal forest in North America and Eurasia (de Groot et al. 2013), with North American forests experiencing less frequent but higher severity fires associated with higher carbon emissions per square meter (van der Werf et al. 2010). Based on the 1997-2009 time period, boreal Eurasia accounts for 71 – 76 % of the total 84,600 km^2 yr^{-1} burned, and 70 – 83 % of the 250 Tg C yr^{-1} released from boreal fire (Balshi et al. 2007, Giglio et al. 2010, van der Werf et al. 2010, Hayes et al. 2011). Average boreal fire return interval is 550 years in North America and 236 years in Eurasia (van der Werf et al. 2010), though many areas experience an average interval of 50 – 180 years (de Groot et al. 2013). The longer period between fires in North America allows higher forest floor fuel loading, resulting in 25 – 53 % higher C emissions per square meter (van der Werf et al. 2010, de Groot et al. 2013). The majority of fires in Eurasian boreal forests are surface fires, limited to burning understory biomass and soil organic material, while the majority in North American boreal forests tend to be crown fires, resulting in greater combustion of tree biomass (Korovin 1996, Stocks et al. 2004). Consequently, combustion of soil organic matter accounts for 58 % of total C emitted from boreal forest fires in North America versus 64 % in Eurasia (Hayes et al. 2011). There are also differences in fire seasonality between the continents, with North American boreal fires occurring primarily in summer and Eurasian boreal forest fires occurring earlier in spring (de Groot et al. 2013).

Patterns of fire in tundra are less well characterized than in boreal systems, due to historically low frequency of fire and remoteness of tundra landscapes (Barrett et al. 2012). Tundra fire return intervals span over two orders of magnitude, from 30 – 5000 years, and are driven by local-scale vegetation and environmental conditions (Higuera et al. 2011). Most tundra ecosystems are susceptible to burn (Rocha et al. 2012), and fire-prone areas experience fire as frequently as the boreal forest, with return intervals of 100 – 300 years (Higuera et al. 2011). Emissions on an areal basis from tundra fire are comparable to those from the boreal forest, reaching 2016 g C m^{-2}, with 60 % of total emissions coming from soil organic matter (Mack et al. 2011). In areas with frequent fire or where fire severity is high, fire can affect long-term ecosystem carbon storage by 10 – 30 %, releasing several decades' worth of accumulated carbon in a single event (Harden 2000, Mack 2011).

Fire's net impact on C balance depends on the amount of C released from combustion, secondary C release due to changes in soil temperature or permafrost, and post-fire successional trajectory (Harden et al. 2000, Mack et al. 2008). Though some vegetation communities are self-replacing after disturbance (Perera et al. 2011), in many boreal systems, vegetation recovery follows predictable stages of succession, typically with fast-growing deciduous species recruiting immediately after burn, followed by a gradual transition, over decades or centuries, to slower growing conifers (Niklasson and Granstrom 2000, Korotkov et al. 2001, Bond-Lamberty et al. 2004, Uotila and Kouki 2005). In the boreal forest, net primary productivity is typically low immediately after fire (1-5 years), highest 10-20 years after disturbance, and moderate after that (Hicke et al. 2003, Bond-Lamberty et al. 2004, Jones et al. 2013). Remotely sensed metrics of primary productivity, such as normalized difference vegetation index (NDVI) and vegetation optical depth (VOD), typically show recovery to pre-fire levels within 3-10 years, though there is substantial variability between fires (Hicke et al. 2003, Goetz et al. 2005, Jones et al. 2013). Field studies show a much slower recovery, with net ecosystem productivity peaking between 6-80 years after fire and biomass still increasing after 150 years (Bond-Lamberty et al. 2004, Harden et al. 2006, Goulden et al. 2011). Pre-fire vegetation, size of burn, and seasonal timing affect the rate and trajectory of succession after fire (Kasischke and French 1997). In tundra ecosystems, primary productivity and biomass typically recover within 5 – 20 years after fire, following transient changes in plant functional groups and community makeup (Wein and Bliss 1973, Fetcher et al. 1984, Racine et al. 1987, Vavrek et al. 1999, Jandt et al. 2008, Bret-Harte et al. 2013). However, large or high-severity tundra fires can result in a shift towards deciduous shrubs and graminoid species, which can persist for decades after the burn, affecting susceptibility to future fire, forage or habitat quality, and ecosystem functioning (Landhausser and Wein 1993, Racine et al. 2004, Jandt et al. 2008, Barrett et al. 2012, Joly et al. 2012, Bret-Harte et al. 2013, Lantz et al. 2013).

Though not the subject of this survey, wildfire also affects net energy balance by changing surface albedo and releasing aerosols in both the arctic tundra and boreal forest (Chambers et al. 2005, Rocha and Shaver 2011, Rocha et al. 2012, Rogers et al. 2012). Depending on the region and time scale, these phenomena can affect overall energy balance as much or more than C-related climate forcing (Rogers et al. 2012).

Response of boreal and arctic wildfire to future change: Boreal and arctic fire may respond to climate change in two temporally distinct but causally linked ways: 1. Changes in weather may affect the flammability of current ecosystems, determining short-term fire extent and emissions, and, 2. On a multi-decadal scale, the distribution of vegetation communities may shift in response to sustained environmental change such as fire, modifying the structural linkage between climate and fire. The short-term response of arctic and boreal fire to climate forcing may depend primarily on changes in regional weather, while the long-term response may depend more on the ultimate redistribution of plant communities throughout the permafrost region.

In both the tundra and boreal forest, vegetation distribution strongly affects flammability. Conversely, fire extent and severity set the stage for succession and vegetation distribution. Two known vegetation-fire feedbacks exist which could potentially increase fire frequency in tundra and reduce fire frequency in the boreal forest. The shift towards shrubs and grass species observed after severe tundra fire could increase tundra biomass and result in more frequent fire (Bret-Harte et al. 2013, Lantz et al. 2013). Paleoclimate data suggest that this has happened in the past (e.g. 13,000-11,000 B.P.), creating large areas of shrub tundra with fire frequency and severity similar to modern boreal systems (Higuera et al. 2008, Higuera et al. 2011). In boreal systems, climate-driven increases in fire can lead to dominance of less-flammable, early successional species, exerting a stabilizing feedback on fire-climate interactions (Beck et al. 2011, Johnstone et al. 2011, Kelly et al. 2013). In past periods of elevated temperature and modified precipitation such as the Medieval Climate Anomaly (1,000-500 B.P.), increases in the area covered by deciduous stands limited fire frequency despite climatic conditions favorable to fire (de Groot et al. 2003, Flannigan et al. 2009, Kelly et al. 2013). However, burning in the past few decades has surpassed fire frequency in parts of the boreal forest for at least the last 10,000 years, suggesting a shift into a new regime of highly active fire (Kelly et al. 2013).

Simulations of future fire regime in the boreal forest and arctic tundra nearly all project an increase in fire extent, severity, and emissions (summarized in Flannigan et al. 2009), however, many uncertainties surrounding vegetation-induced feedbacks on fire still remain, including the effect on vegetation of CO_2 fertilization, nitrogen availability, permafrost degradation, and precipitation (Balshi et al. 2009a, McGuire et al. 2009). Ultimately, future fire behavior in boreal and tundra systems will depend on the interaction between changes in climate as expressed in short-term weather conditions and shifts in vegetation.

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Net ecosystem carbon balance of the permafrost region: hydrologic flux background information[4]

Benjamin W. Abbott, Jeremy B. Jones, University of Alaska Fairbanks
Jorien E. Vonk, Utrecht University

Question: How will organic carbon load and lability change in a warmer world?

System characteristics: The pan-arctic watershed, defined as the drainages of the Arctic Ocean and surrounding seas, covers 20.5 x 10^6 km^2 (Holmes et al. 2012b) and yields 3700 km^3 of discharge annually (McGuire et al. 2009, Holmes et al. 2012a). Worldwide, freshwater ecosystems are active conduits, transporting and transforming globally relevant loads of dissolved and particulate organic carbon (DOC and POC, respectively; Cole et al. 2007, Battin et al. 2009). Freshwater ecosystems play a particularly influential role in regulating carbon cycling at high latitudes, where they cover more than 50% of the landscape in some regions (McGuire et al. 2009) and account for 11% of global runoff, 36% of global lake area, over 50% of global wetland area (Loveland et al. 2000, Lammers et al. 2001, Aufdenkampe et al. 2011, Avis et al. 2011). As permafrost volume shrinks due to climate change, more of the 1670 Pg of organic carbon (C) stored in permafrost region soils (Tarnocai 2009) will thaw and some portion will become available for transport to aquatic ecosystems, depending on changes in local and regional hydrology (Frey and McClelland 2009, O'Donnell et al. 2012, Tank et al. 2012). The response of hydrologic C flux to climate change is a highly uncertain and relatively understudied component of the arctic C cycle (McClelland et al. 2008).

Arctic and boreal environmental change: High latitude air temperature is increasing twice as fast as global mean temperature, due largely to feedbacks associated with sea-ice loss and decrease in snow cover (Holland and Bitz 2003, ACIA 2005, AMAP 2011, Parmentier et al. 2013). Warming has been most prevalent during the autumn and early winter in coastal areas, when sea ice is at its minimum, and in the spring at latitudes from 50° - 60° N as snow cover decreases (AMAP 2011). Growing season length, historically 100 days for tundra and 150 days for boreal forest, has increased 2 – 4 days per decade from 1960 – 2000, due mostly to earlier spring thaw (Euskirchen et al. 2006, Chapin et al. 2011), and is projected to lengthen a total of 37 – 60 days over pre-industrial conditions by the end of the century (Euskirchen et al. 2006, Koven et al. 2011). An intensification of the freshwater cycle is projected across the arctic including increases in precipitation, evapotranspiration (ET), storage, and discharge (Rawlins et al. 2010), however the relative magnitude of these parameters is poorly constrained (Holmes et al. 2012a). Precipitation has increased 5 % over land north of 55° since 1950, though this trend is not significant due to high interannual variability (Peterson et al. 2006, AMAP 2011). Precipitation minus ET is expected to increase 13-25 % by 2100, mostly driven by increases in winter precipitation (Holland et al. 2007, Kattsov et al. 2007), but some areas are expected to experience regional drying (Chapin et al. 2010). While annual discharge is highly variable,

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[4] This document is not intended as a comprehensive or endorsed list of citations or information. It is a partial summary of the current understanding of biomass pools and potential changes to be used as a reference if desired while filling out the arctic and boreal biomass survey.

average pan-arctic discharge has increased 6-10 % since the 1960s and 70s in many regions (Peterson et al. 2002, McClelland et al. 2006, Dery et al. 2009, Overeem and Syvitski 2010).

Changes in air temperature and precipitation have warmed both permafrost and non-permafrost soils over the past century, causing increased active layer thickness, extended freeze-thaw cycling, longer duration of thaw, and widespread ground collapse or thermokarst (Osterkamp and Romanovsky 1999, Hinkel and Nelson 2003, Osterkamp and Jorgenson 2006, Osterkamp 2007, Osterkamp et al. 2009). Models predict widespread near-surface permafrost degradation (in the top 3 m) with projections varying between 40 - 72 % loss by 2100 (Saito et al. 2007, Schaefer et al. 2011, Lawrence et al. 2012). This widespread degradation of permafrost is correlated with increasing winter base flow and the seasonal contribution of ground water relative to surface water (Smith et al. 2007, Walvoord and Striegl 2007, Frey and McClelland 2009). Coupled to changes in hydrology, aquatic chemistry has experienced substantial shifts, including an increase in DOC flux in areas with peat and thick organic soils (Frey and McClelland 2009), a decrease in discharge-normalized DOC where organic soils are shallow (Striegl et al. 2005), increases in major ion concentrations (Frey and McClelland 2009), accelerated chemical weathering (Tank et al. 2012), and increased inorganic nutrient concentrations (McClelland et al. 2007).

Climate change is accelerating thaw and erosion of arctic coastlines due to warming air and water in combination with increased exposure to wave action and storms due to reductions in sea ice cover (IPCC 2007, Stroeve et al. 2007). Thermal collapse and erosion of arctic coastlines delivers DOC and POC to coastal shelf waters, with collapse most pronounced in northeastern Alaska and East-Siberia (Rachold et al. 2000, Jones et al. 2009, Lantuit et al. 2012). Along the Beaufort Sea coast, coastal retreat rates have increased during the last decades (6.8 m yr^{-1} from 1955-1979 to 13.6 m yr^{-1} from 2002-2007; Jones et al. 2009).

Loads and lability: Arctic rivers deliver 36 Tg yr^{-1} of DOC to the ocean, which is 10% of the global terrigenous DOC load (Opsahl et al. 1999), and 6 Tg yr^{-1} of POC (McGuire et al. 2009). It is estimated that another 37-84 Tg yr^{-1} of DOC and 20 Tg yr^{-1} POC are delivered to inland waters but respired to the atmosphere or buried in lakes and streams before reaching the ocean (McGuire et al. 2009, Aufdenkampe et al. 2011), though direct measurements of delivery to inland waters are very scarce. In addition to C carried by inland waters, 18 Tg yr^{-1} or more of POC is released to the Arctic Ocean and surrounding seas from coastal erosion (McGuire et al. 2009, Vonk et al. 2012). In some areas, such as the Eastern Siberian and Laptev Seas, C release from coastal erosion makes up more than half the total C delivery to the ocean (Rachold et al. 2000, Vonk et al. 2012).

Table 1. Organic carbon fluxes in the permafrost region

	DOC (Tg $year^{-1}$)	Riverine POC (Tg $year^{-1}$)	Coastal erosion POC (Tg $year^{-1}$)
Delivery to freshwater ecosystems	100**	20	na
Delivery to Arctic Ocean and surrounding seas	36*	6**	18***

*(Holmes et al. 2012b), **(McGuire et al. 2009), ***sum of coastal erosion POC delivered to ocean from Vonk et al. 2012 and McGuire et al. 2009. Terrestrial to

freshwater delivery of POC was calculated by dividing ocean delivery (6 Tg yr^{-1}) with the downscaled global ratio of 0.75 sedimentation of POC (Aufdenkampe et al. 2011, Battin et al. 2009, McGuire et al. 2009).

Arctic riverine C load is not distributed evenly through the year, with 49% of DOC flux occurring in the two months surrounding peak flow, typically mid-May to mid-July (Finlay et al. 2006, Holmes et al. 2012b). The character, age, and biodegradability of DOC and POC also vary seasonally with more aromatic, labile, and modern C transported in spring and less aromatic, recalcitrant, older C released late in the season, potentially due to differences in thaw depth and transport time (Neff et al. 2006, Holmes et al. 2008). Wintertime DOC can be highly biodegradable (Wickland et al. 2012), though concentrations are typically low (Striegl et al. 2005). Less is known about seasonal patterns of POC, which is typically much older than DOC and potentially more closely linked to permafrost thaw (Guo and Macdonald 2006, Guo et al. 2007).

DOC from surface water in the arctic was once considered inert but recent observations have quantified substantial pools of biodegradable DOC (BDOC). Some rivers transport labile DOC during winter, and BDOC constitutes 20 – 40% of the DOC pool during snowmelt, but less than 10% later in the season (Holmes et al. 2008, Mann et al. 2012, Wickland et al. 2012). These seasonal variations in BDOC are related to DOC composition and nutrient availability (Holmes et al., 2008; Balcarczyk et al., 2009; Mann et al., 2012; Wickland et al., 2012). High biodegradability of snowmelt DOC may be due to fast transport of terrestrially derived DOC to streams early in the season when thaw depth is shallow (Holmes et al. 2008, Wickland et al. 2012), the flush of DOC derived from microbial cells lysed the previous fall during soil freeze-up (Michaelson et al. 1998), and leachate from the previous growing season's leaf litter (Neff et al. 2006, Spencer et al. 2008, Mann et al. 2012). The effect of permafrost regime (areal extent and active layer depth) on DOC yield and biodegradability varies by region, with permafrost extent both positively and negatively correlated with DOC concentrations and lability (Kawahigashi et al. 2004, Striegl et al. 2005, Balcarczyk et al. 2009, Frey and McClelland 2009, Vonk et al. 2013). Biodegradability of permafrost-derived DOC varies from less than 10% DOC loss over 40 days (Balcarczyk et al. 2009) to 34% over 14 days (Vonk et al. 2013), but few estimates are available.

Hydrologic carbon flux response to change: Changes in the hydrologic cycle will affect C transport and processing, however the relationship between hydrology and C load and lability may change non-linearly as the volume of thawed C increases and flowpaths change. The rate of C transport and processing in aquatic systems depends on two related factors: 1. exposure of C to hydrologic export, and 2. biodegradability of thawed C.

As the Arctic warms, C from thawing permafrost will play an increasingly important role governing freshwater and estuarine C and nutrient dynamics through the season. Before permafrost C can enter the modern aquatic C cycle, regardless of its biodegradability, it has to come in contact with surface or ground waters. Because hydraulic conductivity in arctic mineral soils is often very low, much permafrost C may be inaccessible to hydrologic transport even after thaw. However, when soil ice-content is high, permafrost thaw results in ground subsidence, or thermokarst, which can rapidly mobilize sediment, nutrients, and C (Bowden et al. 2008). Thermokarst can release permafrost C from meters below the active layer when exposed on coastal slopes, river banks, lake shores, or hillslopes (Vonk et al. 2012, Cory et al. 2013, Vonk et al. 2013), and may impact watershed-level C biodegradability and nutrient concentrations (Bowden et al. 2008, Woods et al. 2011). Approximately a third of the permafrost region has high ice content (Zhang et al. 1999) and is susceptible to this pathway of catastrophic permafrost collapse upon thaw (Jorgenson et al. 2006).

Little is known concerning mechanistic controls on persistence or processing of modern DOC in arctic and boreal rivers (Mann et al. 2012, Wickland et al. 2012), and even less is known about the behavior of permafrost-derived organic carbon in arctic freshwater and marine ecosystems (Cory et al. 2013, Vonk and Gustafsson 2013). A large portion of bulk soil C in permafrost can be mineralized upon thaw, and much of this mineralized C is from DOC in the soil solution (Dutta et al. 2006, Zimov et al. 2006, Waldrop et al. 2010). DOC from collapsing ice-rich Pleistocene permafrost is very biodegradable (Vonk et al. 2013). However, some DOC released from degrading permafrost is recalcitrant (Balcarczyk et al. 2009), potentially due to differences in permafrost or ground-ice type, previous thaw events, or preferential mineral sorption of hydrophobic C species, which tend to be recalcitrant, during permafrost formation (Kawahigashi et al. 2004). Ultimately, permafrost degradation and ecosystem response to climate change will influence DOC and POC sources as well as hydrologic transportation pathways and storage. These factors together will determine the magnitude and rate of hydrologic C flux from the pan-arctic watershed.

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Biomass survey respondents (* signifies lead expert)

Heather Alexander
Benjamin Bond-Lamberty
Amy L. Breen
M. Syndonia Bret-Harte
F. Stuart Chapin, III*
Han Chen
Jing M. Chen
Torben R. Christensen
J. Hans C. Cornelissen
William de Groot
Ellen Dorrepaal
Howard E. Epstein*
Ned Fetcher
Michael D. Flannigan
Bruce C. Forbes
Scott J. Goetz
Laura Gough
Paul Grogan
Philip E. Higuera
Teresa N. Hollingsworth*
Gustaf Hugelius
Elchin E. Jafarov
Frida Keuper
Peter Kuhry
Michelle C. Mack*
Pertti J. Martikainen
A. David McGuire
Ulf Molau
Susan M. Natali
Steven F. Oberbauer
David Paré
Changhui Peng
Edward B. Rastetter
Martha K. Raynolds
James F. Reynolds
Adrian V. Rocha
Christina Schädel
Kevin Schaefer
Inger K. Schmidt
Gaius R. Shaver
Anatoly Shvidenko
Gregory Starr
Merritt Turetsky*
Tarmo Virtanen
Jeffrey M. Welker
Sergei Zimov

Wildfire survey respondents

Brian W Benscoter
Yves Bergeron
Olivier Blarquez
Benjamin Bond-Lamberty
Amy L. Breen
M. Syndonia Bret-Harte
Christopher Carcaillet
F. Stuart Chapin, III
Han Chen
William de Groot
Thomas H. DeLuca
Michael D. Flannigan*
Nancy H.F. French
Sylvie Gauthier
Martin P. Girardin
Johann G. Goldammer
Philip E. Higuera
Teresa N. Hollingsworth
Feng Sheng Hu
Randi Jandt
Jill F. Johnstone
Eric S. Kasischke
Ryan Kelly
Jari Kouki
Michelle C. Mack
A. David McGuire*
Marc A. Parisien
Serge Payette
Guillermo Rein
Adrian V. Rocha*
Brendan Rogers
Gaius R. Shaver
Anatoly Shvidenko
Merritt Turetsky

Hydrologic carbon flux survey respondents

Benjamin W. Abbott
George R. Aiken
Rainer M.W. Amon
Kevin Bishop
William B. Bowden*
Ishi Buffam
Yihua Cai
Sean K. Carey
Lee W. Cooper
Jacques C. Finlay
Laodong Guo
Tamara K. Harms*
Larry Hinzman
Jeremy B. Jones*
Jan Karlsson
Gerhard Kattner
George W. Kling
Pirkko Kortelainen
Hjalmar Laudon
Isabelle Laurion
Robie W. Macdonald
Paul J. Mann
James W. McClelland
A. David McGuire
David Olefeldt
Oleg S. Pokrovsky
Peter A. Raymond
Robert G.M. Spencer
Robert G. Striegl
Suzanne E. Tank*
Roman Teisserenc
Lars J. Tranvik
Jorien E. Vonk*
Kimberly P. Wickland*
Sergei Zimov